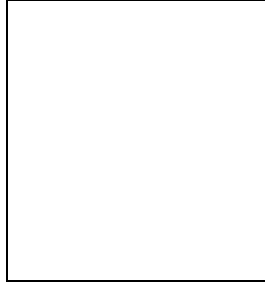


Decays of MSSM Higgs in Flavour-Changing Quark Channels

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We compute the genuine SUSY one-loop quantum contributions to flavour-changing MSSM Higgs-boson decays into $b\bar{s}$ and $s\bar{b}$ using the full diagrammatic approach that is valid for all $\tan\beta$ values and do not rely on the mass-insertion approximation for the characteristic flavour-changing parameter. We analyze in full detail the dependence of these flavour-changing partial widths on all the relevant MSSM parameters and also study the non-decoupling behaviour of these widths with the SUSY mass parameters. We find that these contributions are sizable as compared to the SM ones, and can be very efficient as an indirect method in the future search for Supersymmetry.

1 Introduction

Rare processes involving Flavour Changing Neutral Currents (FCNC), and in particular, the ones related to Higgs physics, provide an extremely useful tool to investigate new physics beyond the Standard Model (SM). In the SM, there is a strong suppression of these FCNC due to the GIM-cancellation mechanism. In contrast, the Minimal Supersymmetric Standard Model (MSSM) provides a natural framework where induced FC scalar interactions could be significant if the soft SUSY-breaking mass terms contain some non-diagonal structure in flavour space.

Here, we are going to concentrate on the neutral MSSM Higgs-boson decays into $b\bar{s}$ and $s\bar{b}$ that are induced by SUSY loop contributions, in a general scenario that includes both possible flavour changing sources, via the Cabibbo-Kobayashi-Maskawa (CKM) matrix and via the misalignment between the quark and squark sectors. We find that these FCNC effects are large, considerably enhanced with respect to the SM contribution, and therefore, they are sensitive to search for indirect SUSY signals. We also checked that our results are perfectly in agreement with the ones of the effective-Lagrangian approach in the large $\tan\beta$ and small FC parameter λ limit.

One of the most important features of these observables are the remaining non-vanishing contributions even in the limit of very heavy SUSY particles and, in addition, that they are enhanced by large $\tan\beta$ factors. Such a non-decoupling behaviour of SUSY particles in the Flavour Changing Higgs Decays (FCHD) can be of special interest for indirect SUSY searches at future colliders, as the forthcoming LHC and a next e^+e^- linear collider, in particular if the SUSY particles turn out to be too heavy to be produced directly.

Here we performed an exact computation of the complete SUSY-QCD and SUSY-EW one-loop contributions from squark–gluino, squark–chargino and squark–neutralino loops to the flavour-nondiagonal decay rates of the three neutral MSSM Higgs bosons, and therefore, our computation is valid for all values of the characteristic parameter measuring the squark-mixing strength λ and for all $\tan\beta$ values.

2 Flavour-changing interactions in the MSSM

In the MSSM there are two sources of FC phenomena. The first one is common to the Standard Model case and is due to mixing in the quark sector. It is produced by the different rotation in the d - and u -quark sectors, and its strength is driven by the off-diagonal CKM-matrix elements. This mixing produces FC electroweak interaction terms involving charged currents and, in particular, in this case, SUSY FC electroweak interaction terms of the chargino–quark–squark type. The second source of FC phenomena is due to the possible misalignment between the rotations that diagonalize the quark and squark sectors. When the squark-mass matrix is expressed in the basis where the squark fields are parallel to the physical quarks (the super-CKM basis), it is in general non-diagonal in flavour space. This quark–squark misalignment produces new FC terms in neutral-current as well as in charged-current interactions.

Assuming that the non-CKM squark mixing is significant only for transitions between the third- and second-generation squarks, and that there is only LL mixing, the squark squared-mass matrix that has to be diagonalized via a 4×4 matrix, $R^{(d)}$, in the $(\tilde{s}_L, \tilde{s}_R, \tilde{b}_L, \tilde{b}_R)$ basis (similarly for the $(\tilde{c}_L, \tilde{c}_R, \tilde{t}_L, \tilde{t}_R)$ basis with rotation matrix $R^{(u)}$), can be written as follows,

$$M_d^2 = \begin{pmatrix} M_{L,s}^2 & m_s X_s & \lambda_{LL} M_{L,s} M_{L,b} & 0 \\ m_s X_s & M_{R,s}^2 & 0 & 0 \\ \lambda_{LL} M_{L,s} M_{L,b} & 0 & M_{L,b}^2 & m_b X_b \\ 0 & 0 & m_b X_b & M_{R,b}^2 \end{pmatrix} \quad (1)$$

where $M_{L,q}^2$, $M_{R,q}^2$ and $m_q X_q$ are the usual flavour preserving entries of the MSSM squark squared mass matrices. The previous assumption (1) is supported on many mSUGRA inspired models.

In our parametrization of flavour mixing in the squark sector, there is only one free parameter, $\lambda_{LL} \equiv \lambda$, that characterizes the flavour-mixing strength. Obviously, the choice $\lambda = 0$ represents the case of zero flavour mixing via misalignment.

After performing the whole diagonalization, we computed the loop-induced flavour-changing neutral Higgs boson decays into second and third generation quarks whose detailed results can be found in ^{1,2}. In the next section we will discuss the dependence of the decay rates and branching ratios on the MSSM parameters and λ .

3 Numerical analysis

Here we numerically estimate the size of the loop-induced FCHD as a function of the MSSM parameters and the mixing parameter λ . The GUT relations $M_3 = \alpha_s/\alpha s_W^2 M_2$ and $M_1 = 5/3 s_W^2/c_W^2 M_2$ are assumed. For the numerical analysis of the FCHD rates, only values of λ (in the range $0 \leq \lambda \leq 1$) that lead to physical squark masses above 150 GeV will be considered.

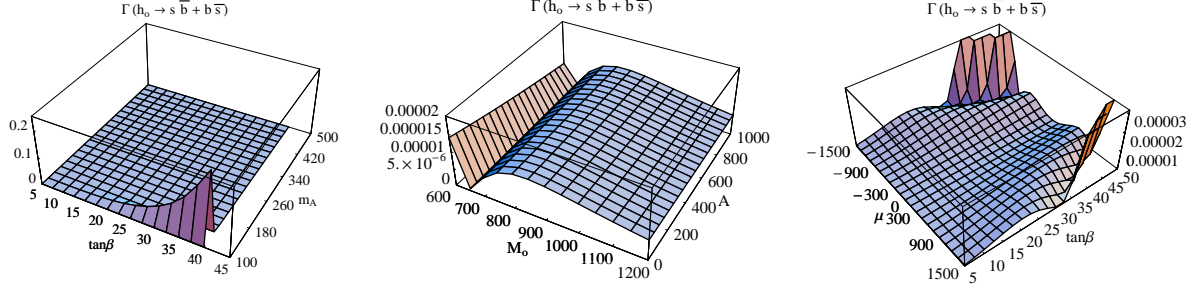


Figure 1: SUSY-QCD $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ (GeV) as a function of $(m_A$ (GeV), $\tan\beta$), $(M_0$ (GeV), A (GeV)) and $(\mu$ (GeV), $\tan\beta$). Fixed values chosen are $\mu = 1500$ GeV, $M_0 = 600$ GeV, $M_{\tilde{g}} = 300$ GeV, $A=200$ GeV, $m_A = 250$ GeV, $\tan\beta = 35$ and $\lambda = 0.5$.

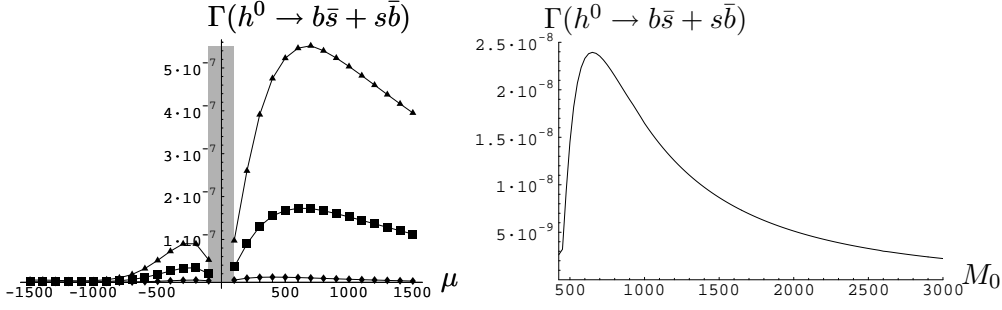


Figure 2: SUSY-EW $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ in GeV as a function of μ (GeV). Triangles, boxes, and diamonds correspond to $m_A = 200, 250, 400$ GeV, respectively (left). $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ as a function of M_0 (right).

The MSSM parameters needed to determine the partial widths $\Gamma(H_x \rightarrow b\bar{s} + s\bar{b})$, for $H_x \equiv h^0, H^0, A^0$, are the following six, m_A , $\tan\beta$, μ , M_2 , M_0 , and A , where we have chosen, for simplicity, M_0 as a common value for the soft SUSY-breaking squark mass parameters, and all the various trilinear parameters, A , to be universal. These parameters were varied over a broad range, and grouped into different pairs in order to visualize the individual dependences of the FCHD widths for each neutral Higgs boson. The most important thing to notice is that we obtain large values of the decay widths. Besides, as expected, the SUSY-QCD contributions dominate by large the SUSY-EW ones, being at least one order of magnitude larger. On the other hand, a common clear behaviour of all three decay widths is the increase with $\tan\beta$, yielding maximal FC effects at large $\tan\beta$ values. In the following we comment shortly on the h_0 and H_0 decay rates. For the A_0 , similar results (not included here) than those for the H_0 , are found.

In fig. 1 we show the behaviour of the SUSY-QCD contributions to $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ with the different MSSM parameters. We can appreciate the above mentioned grow with $\tan\beta$, the expected decrease with M_0 , an approximate symmetric behaviour under $\mu \rightarrow -\mu$, a growing with $|\mu|$ for moderate $\mu < 600$ GeV, and a nearly independence with the trilinear parameter A .

We show in Fig. 2 (left) the behaviour of the SUSY-EW contributions to $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ as a function of the μ parameter for three different values of m_A . The shaded regions in these figures correspond to the region excluded by LEP bounds on the chargino mass $|\mu| < 90$ GeV. The width for the H^0 decay (not shown) is approximately symmetric under $\mu \rightarrow -\mu$, depending of the m_A values, while, as we can see, the $\Gamma(h^0 \rightarrow b\bar{s} + s\bar{b})$ width is more asymmetric with respect to the sign of μ , but all decay widths increase with $|\mu|$ for $|\mu| < 500$ GeV, then reach a maximum, and finally decrease. Regarding the behaviour at very small μ values, we have also found that the widths do not vanish at $\mu = 0$. The origin of this comes entirely from contributions driven by electroweak gauge couplings.

Fig. 2 (right) shows the behaviour of the SUSY-EW h^0 decay as a function of M_0 . The h^0

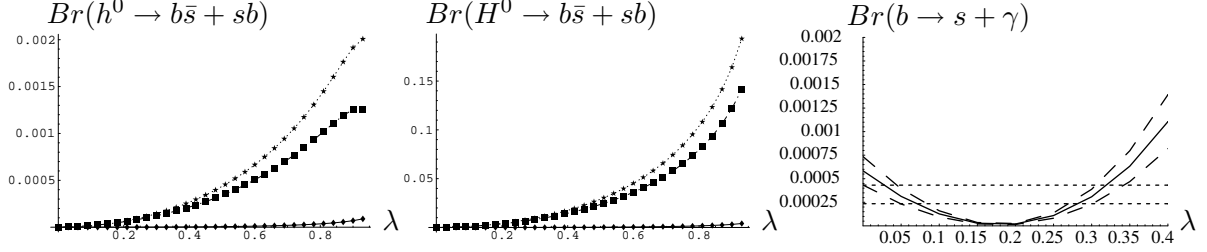


Figure 3: SUSY-EW (Diamonds), SUSY-QCD (stars) and total (boxes) contributions to the $Br(H_x \rightarrow b\bar{s} + s\bar{b})$ $H_x = (h^0, H^0)$ (a) and (b). The prediction for $Br(b \rightarrow s\gamma)$ in the MSSM is shown in (c) as a function of λ for the chosen MSSM parameters specified in the text (solid line). Short-dashed horizontal lines limit the experimental allowed region and long-dashed ones represent the spread out in the MSSM prediction induced by the theoretical uncertainty in the SM contribution of 99 % C.L.⁵.

decay width has a small value for light M_0 due to the fact that chargino and neutralino contributions have opposite sign there. For higher values of M_0 , the neutralino contributions change sign and the partial cancellation disappears, therefore, the decay width increases until it reaches a maximum and then decreases for heavier squarks. The previously mentioned cancellation for small values of M_0 is less obvious for the heavy Higgs, the clearly visible effect is the decrease due to the growing squark masses, which is slower in the latter case.

In the following we study the behaviour of the corresponding FCHD with respect to λ . Investigating the contributions from gluinos, charginos and neutralinos separately, we found that the gluino/neutralino contributions increase monotonically with λ , being exactly zero for $\lambda = 0$, as expected. On the other hand, the contributions from charginos show explicitly the two FC sources, CKM and quark-squark misalignment. In fact, the chargino contribution is different from zero for $\lambda = 0$. The non-zero value at $\lambda = 0$ is due to CKM mixing which is not present in neutralino (or gluino) loops. The CKM effect and the effect of squark mixing compete in the SUSY-EW case in some regions of parameters but for larger values of λ the non-CKM flavour-mixing effect dominates.

In fig. 3 (a) and (b) we can see the SUSY-QCD, SUSY-EW and total contributions for $m_A = 400$ GeV, $\tan\beta = 35$, $M_o = 800$ GeV, $A = 500$ GeV and $M_2 = 300$ GeV. Note that the absolute value for gluino, chargino and neutralino contributions grow with λ separately and that the decay rates of h^0 are much larger for smaller values of m_A and therefore yield larger values of the branching ratio $Br(h^0 \rightarrow b\bar{s} + s\bar{b})$. Notice also that not all values of λ plotted in figs. 3 are compatible with $b \rightarrow s\gamma$ constraints for the chosen values of the MSSM parameters (see fig. 3 (c)). However, we can still find values of λ compatible with $b \rightarrow s\gamma$ that still produce large Higgs branching ratios. For instance, the value $\lambda = 0.3$ is allowed, and the branching ratio is around 2×10^{-4} for h_0 and 10^{-2} for H_0 , which are several orders of magnitude larger than the SM value, $Br(H_{SM} \rightarrow b\bar{s} + s\bar{b}) \sim 4 \times 10^{-8}$ for $m_{H_{SM}} = 114$ GeV. A more exhaustive analysis on the allowed values for the SUSY-QCD corrections of these MSSM Higgs boson branching ratios being restricted from their correlation with the radiative B-meson decays ($b \rightarrow s\gamma$), can be found in⁶.

4 Non-decoupling behaviour of heavy SUSY particles

One important feature of these observables is their non-decoupling behaviour, which means that the FC effects remain non-vanishing even in the most pessimistic scenario of a very heavy SUSY spectrum. The origin of this non-decoupling behaviour in these contributions is the fact that the mass suppression induced by the heavy-particle propagators is compensated by the mass parameter factors coming from the interaction vertices, this being generic in Higgs-boson physics. The non-decoupling contributions to effective FC Higgs Yukawa couplings to quarks

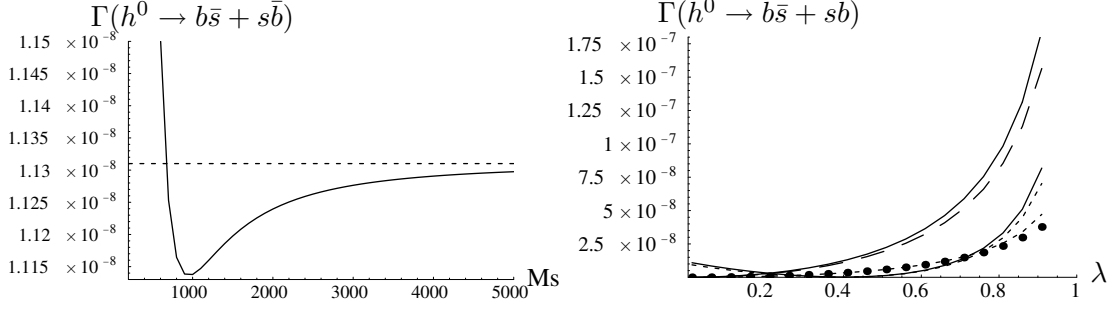


Figure 4: Non-decoupling behaviour of SUSY-EW $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ in GeV with $M_0 = \mu = A = M_{\tilde{g}} = M_S$, $M_1 = \frac{5}{3} \frac{g_2^2}{g_3^2} M_{\tilde{g}}$ and $M_2 = \frac{g_2^2}{g_3^2} M_{\tilde{g}}$, and for $\tan \beta = 35$, $\lambda = 0.5$, $m_A = m_{H^0} = 250$ GeV and $m_{h^0} = 135$ GeV. Exact one-loop results in solid lines and expansions in dashed lines (left). SUSY-EW $\Gamma(h_0 \rightarrow b\bar{s} + s\bar{b})$ as a function of λ (right).

have also been studied in the effective-Lagrangian approach^{3,4}. We will use here instead the full diagrammatic approach which has the advantage of taking into account all SUSY loop contributions (not just the dominant ones) and is valid for all $\tan \beta$ values. Since, on the other hand, we are not using the mass-insertion approximation, our results are more general, being valid for all values of the FC parameter λ . We also checked that our results converge in the large $\tan \beta$ limit and for small λ values to the mass insertion approximation results of the effective Lagrangian approach.

In the following we present the results for the form factors $F_{L,R}$ defined as

$iF = -ig \bar{u}_q [F_L^{qq'}(H)P_L + F_R^{qq'}(H)P_R]v_{q'}H$ in the large M_{SUSY} limit, keeping just the leading $\mathcal{O}(\frac{M_{EW}}{M_{SUSY}})^0$ term in this expansion and where we assume a common M_{SUSY} mass scale,

$$F_{L_{\tilde{g}}}^{(x)} = \frac{\alpha_S}{6\pi} \frac{m_b}{2m_W \cos \beta} \left(\sigma_2^{(x)} + \tan \beta \sigma_1^{(x)*} \right) F(\lambda)$$

$$F_{L_{\tilde{\chi}^\pm}}^{(x)} = \frac{\alpha_{EW}}{4\pi} \frac{m_b}{2m_W \cos \beta} \left[\frac{1}{8m_W^2 \sin^2 \beta} \left[\left(V_{CKM}^{tb} V_{CKM}^{cs} m_c^2 + V_{CKM}^{cb} V_{CKM}^{ts} m_t^2 \right) F(\lambda) \right. \right.$$

$$+ \left(V_{CKM}^{cb} V_{CKM}^{cs} m_c^2 + V_{CKM}^{tb} V_{CKM}^{ts} m_t^2 \right) J(\lambda) \left. \right] - \frac{1}{4} \left[\left(V_{CKM}^{cb} V_{CKM}^{cs} + V_{CKM}^{tb} V_{CKM}^{ts} \right) J(\lambda) \right.$$

$$\left. \left. + \left(V_{CKM}^{cb} V_{CKM}^{ts} + V_{CKM}^{tb} V_{CKM}^{cs} \right) F(\lambda) \right] \right] \left(\sigma_2^{(x)} + \tan \beta \sigma_1^{(x)*} \right), \quad (2)$$

$$F_{L_{\tilde{\chi}^0}}^{(x)} = -\frac{\alpha_{EW}}{4\pi} \frac{m_b}{2m_W \cos \beta} \left[\frac{1}{8} \left(1 + \frac{5}{9} \tan^2 \theta_W \right) \left(\sigma_2^{(x)} + \tan \beta \sigma_1^{(x)*} \right) \right] F(\lambda), \quad (3)$$

where, $F(\lambda) = \frac{2}{\lambda^2} [(\lambda+1) \ln(\lambda+1) + (\lambda-1) \ln(1-\lambda) - 2\lambda]$, $J(\lambda) = \frac{2}{\lambda^2} [(\lambda+1) \ln(\lambda+1) - (\lambda-1) \ln(1-\lambda)]$, $\sigma_1^{(x)} = (\sin \alpha, -\cos \alpha, i \sin \beta)$ and $\sigma_2^{(x)} = (\cos \alpha, \sin \alpha, -i \cos \beta)$. The results for F_R are like the previous ones but replacing $m_b \rightarrow m_s$, $m_c \rightarrow m_t$ and taking the complex conjugate.

In the following, we show graphically some of the main features. For brevity, we choose to show in fig. 4 just the SUSY-EW contributions but the SUSY-QCD ones behave in a similar way. We can see that, for large values of $M_S \equiv M_{SUSY}$, the exact partial widths tend to a non-vanishing value, characteristic of the non-decoupling behaviour. Besides, the exact results are very well described, even for moderate M_S values (say ≥ 600 GeV), by our previous asymptotic results, which make these short formulas very useful for future phenomenological Higgs boson studies.

The dependence of the total chargino and neutralino contributions on the FC parameter λ are shown in Fig. 4 (right). The exact one-loop chargino (neutralino) contribution is plotted in solid (dotted) lines and the dashed lines correspond to their approximate asymptotic results, given by the previous formulas. The lower lines take into account both possible FC effects

while the upper ones correspond to the charginos contribution setting $V_{CKM} = I$. We can appreciate that these effects interfere destructively. We can also see that the neutralino and chargino contributions depend strongly on the chosen parameters and can be comparable in size for a large range in λ , therefore, neglecting the neutralino contribution, as usually done in the literature, is not a good approximation.

Regarding the so-called decoupling limit where $m_A \gg m_{EW}$, we see clearly that the SUSY loop contributions, in the h_0 case, go to zero, recovering, as expected, the SM result.

5 Conclusions

We have computed the genuine SUSY one-loop quantum effects to flavour-changing MSSM Higgs-boson decays into second and third generation quarks using the full diagrammatic approach and therefore our results are valid for all $\tan\beta$ values and for all values of the flavour-mixing parameter λ . We find that for moderate $\tan\beta$ and λ values, some of the contributions usually neglected in the effective-Lagrangian approach can be sizable and, therefore, a realistic estimate of the branching ratios should rely better on the full diagrammatic approach. After analyzing in full detail the dependence of the FCHD partial widths, with all the relevant MSSM parameters and λ , we found large rates and these are very sensitive to $\tan\beta$, μ , and λ . The branching ratios grow with both $\tan\beta$ and λ and reach quite sizable values in comparison with the SM ones, in the large $\tan\beta$ and λ region. For instance, for the following choice allowed by the $b \rightarrow s\gamma$ constrains, $\lambda = 0.3$, $\tan\beta = 35$, $m_A = 400$, $M_o = 800$ GeV, $A = 500$ GeV and $M_2 = 300$ GeV, we found branching ratios of $\mathcal{O}(10^{-4})$ for the h^0 and $\mathcal{O}(10^{-2})$ for the A^0 and H^0 , which are both some orders of magnitude larger than $Br_{SM} \approx \mathcal{O}(10^{-8})$. As expected, the SUSY-EW contributions are subdominant with respect to the SUSY-QCD ones, but they contribute with opposite sign and important interference effects, which modify the SUSY-QCD effects remarkably, appear.

An interesting feature of these radiative contributions is their non-decoupling behaviour for large values of the SUSY particle masses, *i.e.*, even in the most pessimistic scenario of very large SUSY mass parameters, FC effects remains and they can be sizable (a set of analytical asymptotic results can be found in refs. ^{1,2}).

In conclusion, the results presented in this talk indicate that FCHD constitute an interesting scenario for indirect searches of supersymmetry, with important contributions in some regions of the MSSM parameter space, that remain even for a very heavy SUSY spectra.

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